NRL Report 7299

UNCLASSIFIED

Comparison of Plane-Stress Fracture Toughness for Three Aluminum Sheet Alloys

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August 11, 1971

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ABSTRACT

A program for evolving analytical procedures to characterize the fracture resistance of high-strength sheet metals has been initiated. The first phase of this program is concerned with the development of a standard plane-stress (K_c) test method for reliable characterization of high-strength sheet alloys. The test incorporates fracture mechanics principles to define the relationship between the stress and critical crack size at instability in terms of a single parameter K_c. A center-cracked sheet panel has been selected as the most promising test-specimen configuration to investigate this relationship.

In conjunction with studies of specimen geometry factors affecting the K_c value, the K_c test has been applied to three high-strength, thin-sheet aluminum alloys: 7075-T6, 7178-T6, and a new alloy, 7475. Two specimen variables, width and crack length, were investigated to determine their influence on the fracture-toughness parameter. The results indicate that whereas all of these alloys are subject to unstable fracture emanating from relatively small cracks, the two tempers of the 7475 alloy manifest K_c values 50 percent higher than that of the 7178-T6 or 7075-T6 alloys. This higher fracture resistance is reflected in the considerably larger critical crack length which can be obtained in the 7475 alloy before commencement of unstable crack propagation.

PROBLEM STATUS

This report completes one phase of the problem. Work on other aspects of the problem is continuing.

AUTHORIZATION

NRL Problem M01-24
Project RR 007-01-46-5431

Manuscript submitted May 3, 1971.

COMPARISON OF PLANE-STRESS FRACTURE TOUGHNESS FOR THREE ALUMINUM SHEET ALLOYS

INTRODUCTION

Ultrahigh-strength, thin-sheet alloys are characterized by low fracture toughness, which will permit a small crack to become unstable when the sheet is loaded within the elastic stress region. Whether the propagating crack is arrested or continues unstable propagation depends on the relationship between the fracture extension force driving the crack and the fracture extension resistance of the metal.

Ultrahigh-strength aluminum alloys are widely used in military and commercial aircraft. The most common alloys for this application are the aluminum-copper (2000) series and the aluminum-zinc-magnesium (7000) series. These alloys are heat treatable to high-strength levels which manifest a low resistance to crack propagation. This report describes a fracture toughness test used to measure the fracture resistance of three 7000-series alloys. The fracture toughness of these ultrahigh-strength alloys will be compared in terms of the critical-crack-size and stress required for fracture.

EXPERIMENTAL PROCEDURE

Materials

Three ultrahigh-strength aluminum alloys were investigated: 7075-T6, 7178-T6, and a recently developed alloy, 7475. The available quantity of this last alloy was limited to two 24-by-24-in. sheets which were 0.090 in. thick. One sheet was heat treated to a T61 temper, and other sheet received an additional aging treatment of 15 to 18 hours at 325°F to provide a T761 temper.

The mechanical properties of the alloys are presented in Table 1. The yield-strength (YS) values of 7075-T6 and 7178-T6 were similar, 76.5 and 78.9 ksi respectfully, whereas the YS of 7475 ranged from 58.6 to 61.5 ksi.

Table 1
Mechanical Properties of the Al Alloys

Alloy-Temper	Fracture Direction	Sheet Thickness (in.)	Tensile Strength (ksi)	Yield Strength at 0.2% Offset (ksi)	Elongation (%)
7178-T6	RW or WR	0.063	88.7	78.9	9.9
7075-T6	RW or WR	0.063	88.5	76.5	10.9
7475-T61	WR	0.090	70.4	59.3	12.5
	RW	0.090	69.8	61.5	11.5
7475-T761	WR	0.090	70.5	58.6	10.5
	RW	0.090	70.0	60.7	11.5

Test Method

For ultrahigh-strength metals the likelihood that a crack will undergo instability depends on the critical relationship between the size of the crack and the stress acting on the segment of the structure in which the crack is embedded. The fracture-mechanics relationship which predicts the size of the crack required for the onset of rapid fracture at a particular applied stress is

$$K_c = f(\sigma_f, a_c), \tag{1}$$

where σ_f is failure stress, a_c is one-half of the critical crack, and K_c is the plane-stress, fracture-toughness parameter. The K_c parameter provides in a single term the resistance of a metal sheet to crack instability.

At the present time there is no standard fracture-toughness test for determinating the stress-and-critical-crack-length relationships in these low-toughness sheet metals. To evolve standard test procedures, a renewed effort has been initiated to explore the influence of specimen dimensional variables. Because the stress analysis of the center-cracked sheet panel is well documented (1) and the testing procedure well adapted for laboratory use, the center-cracked specimen was selected for these studies.

The center-cracked-tension (CCT) specimen is shown in Fig. 1. The sheet specimen was positioned between the grips of a tensile machine prior to application of the load. In the center of the specimen a cracklike slit was introduced by an electric discharge, and a beam-displacement gage instrumented with a four-strain-gage cricuit was placed within the slit (Fig. 2). On loading, the borders of the slit were displaced and cracks developed from the slit tips along a plane perpendicular to the applied stress. The displacement gage monitored the crack-opening displacement (COD) via an electrical readout to an XY recorder; a previous calibration between COD and crack length enabled calculation of the crack length at any point during the test (2). Stable crack growth occurred from each slit tip until the total crack reached a critical length for the applied stress, whereupon unstable crack propagation ensued and the specimen fractured. The crack length and stress at the onset of instability were determined, and K_c was calculated.

A designer can employ the K_c value of the particular alloy in two ways: (a) the toughness of candidate alloys may be compared to allow a more rational selection in the choice of a fracture-resistant alloy for a particular application, and (b) the fracture-stress-and-critical-crack-length relationship can be calculated for the selected metal to permit prediction of the conditions at which crack instability will begin.

DISCUSSION OF RESULTS

Effect of Specimen Dimensions on K_c

Specimens for the K_c tests of the 7075 and 7178 alloys were prepared by cutting the sheets into panels 12 in. wide by 36 in. long. A slit was cut in the center of each panel with an electric discharge. The width W of the slit was 1/16 in., and the slit length 2a varied between 2a/W = 0.04 and 2a/W = 0.6. The slit tip radius approximated 0.002 in.; the slits were not extended by fatigue cracks, since the stable crack growth preceding fracture provided the sharp crack necessary to measure K_c. The limited quantity of 7475 alloy required the use of foreshortened specimens 12 in. wide by 12 in. long. To achieve the desired specimen length, a row of holes was drilled near the top and bottom edges of the specimen, and extension tabs were fastened to the specimen with bolts. Previous K_c tests on foreshortened aluminum specimens which were lengthened by extension tabs indicated that the K_c value was unaffected by this technique (2).

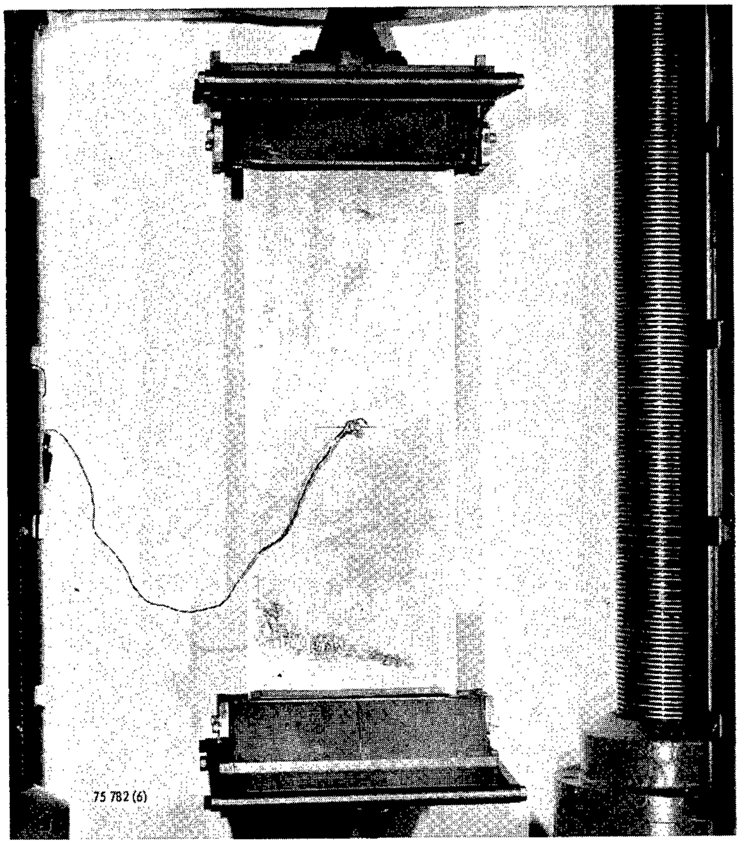

Fig. 1 - A 12-in.-wide K_c specimen positioned in the tensile machine grips. The beam displacement gage is inserted in the center slit to monitor crack opening displacement, which permits the calculation of crack extension.

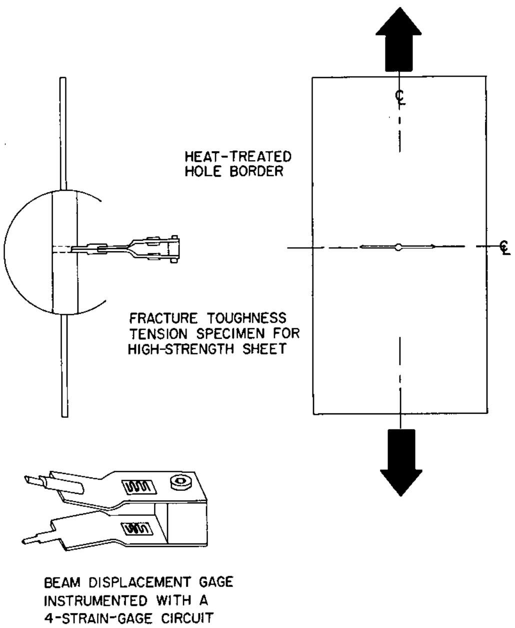

Fig. 2 - The instrumented beam displacement gage used in the K_c test

The 12-in. panel width was chosen at the commencement of the investigation as a reasonable and conservative size that should be large enough to eliminate specimen width as a test variable. To ensure that K_c would not be affected by the width dimension, specimens were prepared from the 7075 and 7178 alloys which were 3, 6, 9, and 12 in. wide. The original slit length 2a was held to approximately one-third of the width (2a/W ≈ 1/3) for each specimen.

The results of the study on specimen geometry factors are presented in detail in Ref. 2 and summarized in Fig. 3. The data for the 7178-T6 alloy denote that the average K_c value of 55.4 ksi-$\sqrt{\text{in.}}$ is unchanged as the specimen width is decreased from 12 in. to 3 in. Likewise, the average K_c value of 65.2 ksi-$\sqrt{\text{in.}}$ for the 7075-T6 alloy is independent of the width dimension over this range. Thus the 12-in. specimen width for the 7475 sheet specimens appeared adequate for valid K_c measurements.

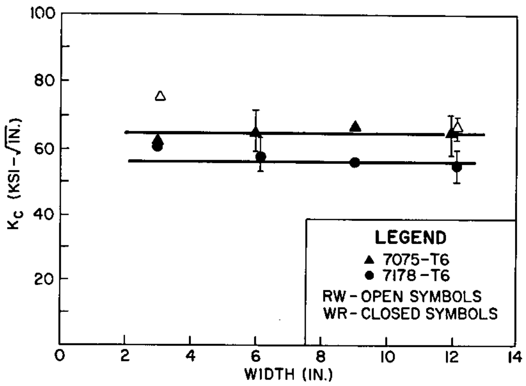

Fig. 3 - Relationship between K_c and specimen width for two high-strength aluminum alloys

Another specimen variable which can influence K_c is the length of the crack at instability. On the basis of other investigations (3), center cracks which are too short or too long provide erroneous K_c measurements. A test series for specimens of different widths was initiated to determine the range over which K_c would be unaffected by crack length. Lightweight restraint plates lined with Teflon sheet were used to prevent buckling. As shown in Fig. 4, the original slit length ($2a_0$) was varied for 12-in.-wide specimens of these ultrahigh-strength aluminum alloys. The original length of the slit ranged from 0.5 in. to 7 in. ($0.04 < 2a_0/W < 0.6$). The curves of Fig. 2 indicate that data scatter is increased for the 7075 and 7178 alloys when the final-crack-length/width ratio 2a/W approaches 0.1 or less. For the very large cracks, 7075 alloy showed no scatter at 2a/W = 0.5, which represents a 6-in.-long crack in a 12-in.-wide specimen, but the data scatter was excessive for the 7178 alloy once the crack exceeded a 2a/W = 0.5. Whereas further experiments could delineate with greater accuracy the trends of the scatter for the very long and very short cracks, it can be concluded that as long as the 2a/W value at instability is greater than 0.15 and less than 0.50, the particular crack length will not affect K_c for these alloys.

Fracture Toughness Properties

Based on the data reflecting the influence of 2a/W on K_c for 7075-T6 and 7178-T6 alloys, slit lengths of 2.0 and 3.0 in. ($2a_0/W$ = 0.18 to 0.25) were chosen for the two tempers of the 7475 alloy. The fracture toughness properties of these three alloys are presented in Table 2. Due to the limited quantity of 7475 material, the K_c value of each fracture direction (WR and RW) for each temper (T61 and T761) was established with two specimens

Table 2
Fracture Toughness Data for the Al Alloys

Alloy-Temper	Fracture Direction	Yield Strength (YS) (ksi)	K_c (ksi-$\sqrt{in.}$)	K_c/YS ($\sqrt{in.}$)	Critical Crack Length at Different Stress Levels (in.)		
					YS/2	3(YS)/4	YS
7178-T6	RW or WR	78.9	55.4	0.70	1.29	0.57	0.32
7075-T6	RW or WR	76.5	65.2	0.85	1.87	0.83	0.47
7475-T61	WR	59.3	88.4	1.49	5.71	2.53	1.42
	RW	61.5	93.6	1.52	5.91	2.64	1.48
7475-T761	WR	58.6	91.6	1.56	6.26	2.77	1.56
	RW	60.7	98.4	1.62	6.71	2.99	1.68

for each condition, e.g., two specimens were used to determine K_c for the 7475-T61 alloy in the RW direction.

For the 7475 alloy, little difference in toughness is observed between the two tempers. The T61 temper evidences slightly lower resistance to fracture in a specified fracture direction than is measured in the T761 temper. For both tempers, the WR fracture direction (short longitudinal) indicates a slightly lower K_c than does the RW direction. Whereas all of the data points are plotted for this alloy in Fig. 4, a single line is drawn through them to represent the average K_c of both tempers and both fracture directions.

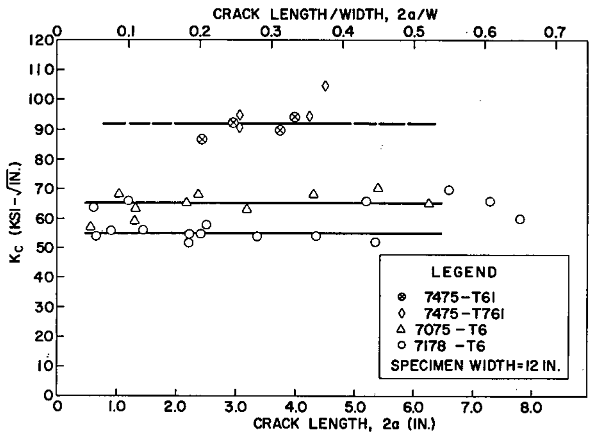

Fig. 4 - K_c as a function of crack length at instability. Data scatter for 7178-T6 and 7075-T6 increases when the ratio of crack length at instability to width is less than 0.15 and greater than 0.50.

The K_c data in Table 2 signify that the fracture resistance of the 7475 alloy is approximately 50 percent higher than that of the 7075-T6 or 7178-T6 alloys. This higher fracture resistance is reflected in the much larger critical crack length which can exist in the sheet stressed to a specified fraction of its yield strength before unstable fracture commences. The right-hand columns of Table 2 indicate the critical crack length for each alloy and temper when the sheet is loaded to 50%, 75%, and finally to 100% of its yield stress. For instance, when the 7178-T6 sheet is stressed to 75% yield strength, a 0.57-in.-long crack will initiate catastrophic fracture of the sheet. A crack as long as 2.6 in. is required for instability in the 7475-T61 (RW) alloy under the same level of applied stress. Whereas the 7178-T6 and 7075-T6 alloys are subject to brittle fracture from relatively small cracks, the 7475 alloy manifests much greater resistance to crack propagation under elastic stresses.

The greater fracture toughness of the 7475 alloy was also evident when the test record was replotted to compare applied load on the specimen to crack growth. When any of these alloys are loaded in tension, the stress must reach a certain value before a crack will form at the slit tip. This load region which precedes crack initiation has been designated Region I in Fig. 5. Once the crack is initiated, it will grow in a stable manner under a rising load (Region II); if the load is held constant, the crack will become arrested within Region II. For the more brittle 7075-T6 and 7178-T6 alloys, once the crack has grown to a critical length, stable crack growth will give way to unstable fracture, leading to instantaneous fracture of the specimen.

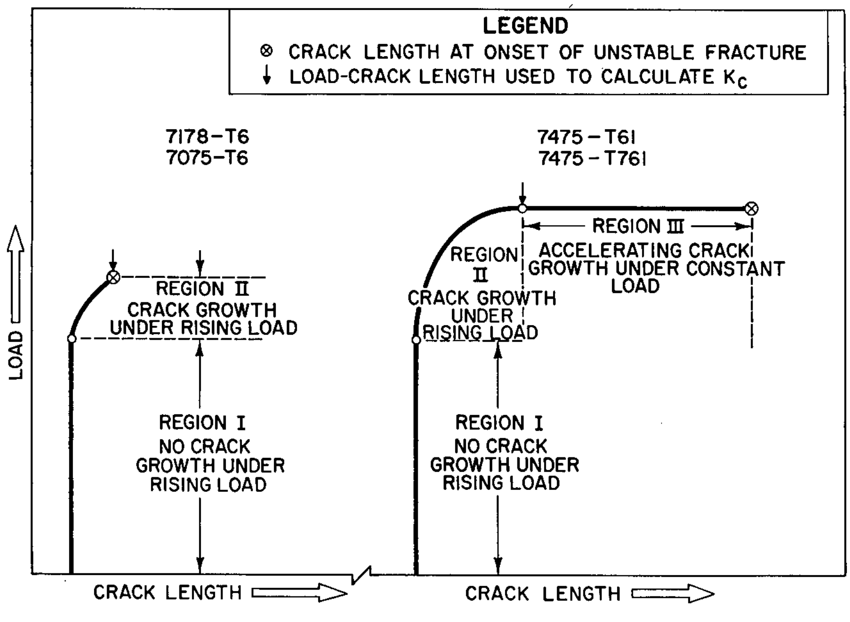

Fig. 5 - Replotted test record which compares the crack growth behavior of the very-low-toughness alloys (7178-T6 and 7075-T6) and slightly tougher metal (7475). The phenomenon of crack growth under a constant load for the 7475 alloy may be characteristic of moderately tough alloys which fail under elastic stresses.

Though the tougher 7475 alloy shares Region I and II behavior with the more brittle alloys, fracture does not occur under a rising load. Instead, after the crack has slowly grown some distance under a rising load, the crack velocity will markedly increase while the load on the specimen remains constant. The crack will extend at an increasing velocity until instability results in fracture of the specimen. For practical purposes the point at which the crack begins to grow under a constant load, the beginning of Region III, marks the limit of structural integrity. Therefore the crack length at the beginning of this region, denoted by the arrow in Fig. 5, is used to calculate K_c.

The relationship between gross-failure stress and crack length at instability is presented in Fig. 6 for the 7075 and 7178 alloys and for the two tempers of the 7475 alloy. It is obvious that even a small crack precipitously decreases the failure stress. A constant K_c curve has been drawn through the data points of each alloy. Data scatter is minimal when 2a/W is held between 0.1 and 0.5.

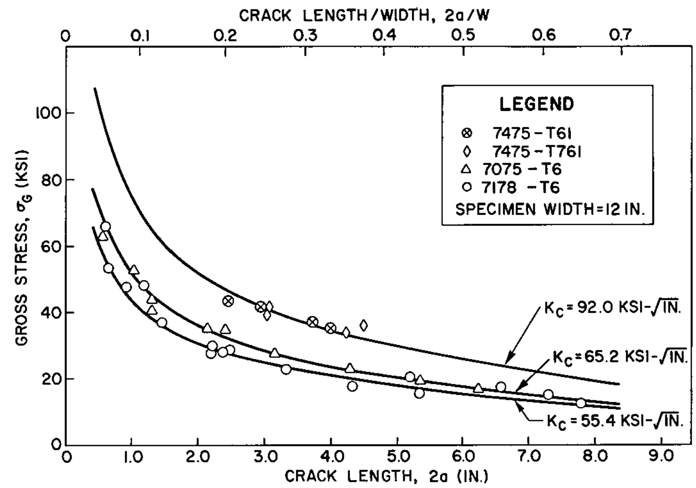

Fig. 6 - The failure-stress-and-critical-crack-length relationship for the three high-strength aluminum alloys

The curves of Fig. 6 demonstrate that the lowest fracture toughness is evidenced by 7178-T6 alloy, followed in order of increasing fracture resistance by the 7075-T6 and 7475 alloys. For example, at a crack length of 1.5 in. the stress at which instability would be initiated is 36 ksi in 7178 alloy and 42 ksi in 7075 alloy, whereas an applied stress of 60 ksi is required to commence unstable propagation in the 7475 series. No attempt was made to distinguish among the 7475-alloy tempers, due to the limited number of specimens investigated and the apparent closeness of the K_c values for both tempers.

SUMMARY

A program has commenced to standardize a test method based on fracture-mechanics principles which will permit the measurement of the fracture resistance of high-strength sheet alloys. The K_c values measured by such a test have the unique capability of being used to compare the relative toughness of thin sheet alloys, as well as to define the stress-and-crack-length relationship at which unstable crack propagation will occur.

This work represents the first step in the evolution of analytical procedures to characterize fracture resistance of high-strength sheet metals. These procedures will allow engineering predictions of structural performance in relation to flaw-size and stress factors. The application of this test method to a broad spectrum of metal alloys will permit the employment of the analytical procedures to improve metal quality and the interpretation of failure-safe design.

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

COMPARISON OF PLANE-STRESS FRACTURE TOUGHNESS FOR THREE ALUMINUM SHEET ALLOYS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
A final report on one phase of the NRL problem.

5. AUTHOR(S) *(First name, middle initial, last name)*

Charles N. Freed, Anna M. Sullivan, and Joseph Stoop

6. REPORT DATE August 11, 1971	7a. TOTAL NO. OF PAGES 11	7b. NO. OF REFS 3
8a. CONTRACT OR GRANT NO. NRL Problem M01-24 b. PROJECT NO. RR 007-01-46-5431 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7299 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy Office of Naval Research Arlington, Virginia 22217

13. ABSTRACT

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DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

UNCLASSIFIED

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ultrahigh-strength alloys						
Aluminum sheet alloys						
Plane stress fracture toughness						
Crack propagation						
Unstable fracture						